Measurement of the CP Asymmetry in $B \to X_s\gamma$

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arXiv:hep-ex/0308038v4 22 Jul 2004

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Abstract

Direct CP violation in the $b \to s\gamma$ process is a sensitive probe of physics beyond the Standard Model. We report a measurement of the CP asymmetry in $B \to X_s\gamma$, where the hadronic recoil system X_s is reconstructed using a pseudo-reconstruction technique. In this approach there is negligible contamination from $b \to d\gamma$ decays, which are expected to have a much larger CP asymmetry. We find $A_{CP} = 0.002 \pm 0.050(\text{stat.}) \pm 0.030(\text{syst.})$ for $B \to X_s\gamma$ events having recoil mass smaller than 2.1 GeV/c^2. The analysis is based on a data sample of 140 fb^{-1} recorded at the $\Upsilon(4S)$ resonance with the Belle detector at the KEKB e^+e^- storage ring.

PACS numbers: 11.30.Er, 13.20.He, 14.40.Nd

Radiative B decays, which proceed mainly through the $b \to s\gamma$ process, have played an important role in the search for physics beyond the Standard Model (SM). The inclusive branching fraction has been measured by CLEO [1], ALEPH [2] and Belle [3], giving results consistent with the recent theoretical prediction of $(3.57 \pm 0.30) \times 10^{-4}$ [4]. The SM predicts very small direct CP violation in $b \to s\gamma$; the CP asymmetry,

$$A_{CP}(b \to s\gamma) = \frac{\Gamma(b \to s\gamma) - \Gamma(\bar{b} \to \bar{s}\gamma)}{\Gamma(b \to s\gamma) + \Gamma(\bar{b} \to \bar{s}\gamma)},$$

is about $+0.5\%$ in the SM, while some new physics, such as supersymmetry, allows the CP asymmetry to be above 10% without changing the inclusive branching fraction [5]. Thus, measurement of A_{CP} may provide information on new physics that cannot be extracted from the measurement of the branching fraction. Previously, CLEO measured $-0.27 < 0.965 A_{CP}(b \to s\gamma) + 0.02 A_{CP}(b \to d\gamma) < 0.10$ at 90% confidence level [6]; however $b \to d\gamma$ is expected to cancel the CP asymmetry in $b \to s\gamma$ [7]. The measurement presented here has negligible $b \to d\gamma$ contamination.

In this paper, we report on a measurement of the CP asymmetry in $B \to X_s\gamma$, where the hadronic recoil system X_s is reconstructed using a pseudo-reconstruction technique. The analysis is based on 140 fb^{-1} of data taken at the $\Upsilon(4S)$ resonance (on-resonance) and 15 fb^{-1} at an energy 60 MeV below the resonance (off-resonance), which was recorded by the Belle detector [8] at the KEKB asymmetric e^+e^- collider (3.5 GeV on 8 GeV) [9]. The on-resonance data correspond to 152 million $B\bar{B}$ events. The Belle detector has a three-layer silicon vertex detector, a 50-layer central drift chamber (CDC), an array of aerogel Cherenkov counters (ACC), time-of-flight scintillation counters (TOF) and an electromagnetic calorimeter of CsI(Tl) crystals (ECL) located inside a superconducting solenoid coil that provides a 1.5 T magnetic field. An instrumented iron flux-return for K_L/μ detection is located outside the coil.

We form the hadronic recoil system, X_s, with a mass up to 2.1 GeV/c^2, by combining one charged or neutral kaon with one to four pions, where at most one pion can be neutral. We also reconstruct X_s via $K^\pm K^\mp K^\pm (\pi^\mp)$ and $K_S^0 K^\pm K^\mp (\pi^\pm)$ including the $B \to K\phi\gamma$ decays that were observed recently by Belle [10].

Each of the primary charged tracks is required to have a momentum in the e^+e^- center-of-mass (CM) frame that is greater than 100 MeV/c, and to have an impact parameter within ± 5 cm of the interaction point along the positron beam axis and within 0.5 cm in the transverse plane. These tracks are identified as pion or kaon candidates according to a likelihood ratio based on the light yield in the ACC, the TOF information and the specific ionization measurements in the CDC. For the selection applied on the likelihood ratio, we obtain an efficiency (pion misidentification probability) of 90% (7%) for charged kaon candidates, and an efficiency (kaon misidentification probability) of 93% (7%) for charged pion candidates. Tracks that are identified as an electron or muon are excluded.

K_S^0 candidates are formed from $\pi^+\pi^-$ combinations whose invariant mass is within 8 MeV/c^2 of the nominal K_S^0 mass. The two pions are required to have a common vertex that is displaced from the interaction point. The K_S^0 momentum direction is also required to be consistent with the K_S^0 flight direction. Neutral pion candidates are formed from pairs of photons that have an invariant mass within 16 MeV/c^2 of the nominal π^0 mass and an opening angle smaller than 60°. Each photon is required to have an energy greater than 50 MeV. A mass constrained fit is then performed to obtain the π^0 momentum.

The B meson candidates are reconstructed from the X_s system and the highest energy photon with a CM energy between 1.8 and 3.4 GeV within the acceptance of the barrel ECL

$(33° < \theta_\gamma < 128°$, where θ_γ is the polar angle of the photon in the laboratory frame). In order to reduce the background from decays of π^0 and η mesons, we combine the photon candidate with all other photons in the event and reject the event if the invariant mass of any pair is within 18 MeV/c^2 (32 MeV/c^2) of the nominal π^0 (η) mass.

We use two independent kinematic variables for the B reconstruction: the beam-energy constrained mass $M_{\mathrm{bc}} \equiv \sqrt{(E^*_{\mathrm{beam}}/c^2)^2 - (|\vec{p}^{\,*}_{X_s} + \vec{p}^{\,*}_\gamma|/c)^2}$ and $\Delta E \equiv E^*_{X_s} + E^*_\gamma - E^*_{\mathrm{beam}}$, where E^*_{beam} is the beam energy, and $\vec{p}^{\,*}_\gamma$, E^*_γ, $\vec{p}^{\,*}_{X_s}$, $E^*_{X_s}$ are the momenta and energies of the photon and the X_s system, respectively, calculated in the CM frame. In the M_{bc} calculation, the photon momentum is rescaled so that $|\vec{p}^{\,*}_\gamma| = (E^*_{\mathrm{beam}} - E^*_{X_s})/c$ is satisfied; this improves the M_{bc} resolution to 2.9 MeV/c^2. We require $M_{\mathrm{bc}} > 5.24$ GeV/c^2 and -150 MeV $< \Delta E < 80$ MeV. We define the signal region to be $M_{\mathrm{bc}} > 5.27$ GeV/c^2.

The largest source of background originates from continuum $e^+e^- \to q\bar{q}$ ($q = u, d, s, c$) production including contributions from initial state radiation ($e^+e^- \to q\bar{q}\gamma$). In order to suppress this background, we require the presence of a high energy lepton from the opposite B. The lepton can be either an electron with a CM momentum greater than 0.8 GeV/c or a muon with a laboratory momentum greater than 1.0 GeV/c. In both cases, the opening angle $\theta^*_{\ell\gamma}$ between the high energy photon from the signal B meson and the lepton, calculated in the CM frame, must satisfy $|\cos\theta^*_{\ell\gamma}| < 0.8$. In addition to this lepton requirement, we use the likelihood ratio described in Ref. [11], which utilizes the information from a Fisher discriminant [12] formed from six modified Fox-Wolfram moments [13] and the cosine of the angle between the B meson flight direction and the beam axis. The lepton requirement (likelihood ratio selection) retains 15% (92%) of the signal, rejecting 98.5% (55%) of the $q\bar{q}$ background.

When multiple B candidates are found in the same event, we take the candidate that gives the highest confidence level when we fit the X_s decay vertex, constrained to the profile of the measured interaction region. The confidence level for the $K^0_S\pi^0\gamma$ mode is set to zero, because we do not determine the vertex. If multiple B candidates appear in an event according to the inclusion or omission of different π^0 mesons in the X_s recoil system, we take the candidate that has the minimum $|\Delta E|$.

We fit the M_{bc} distribution to extract the signal yield. The M_{bc} distribution of the $q\bar{q}$ background is modeled by an ARGUS function [14] whose shape is determined from the off-resonance data. (The lepton requirement is not applied to the off-resonance data in order to compensate for the limited amount of data in that sample.) Background from B decay is divided into two components. B decays through $b \to c$ transitions (except color-suppressed B decays such as $B^0 \to \bar{D}^0\pi^0$), which we call $B\bar{B}$ background in this paper, have a non-peaking M_{bc} distribution which is modeled by another ARGUS function. Rare B decays, i.e. B decays through $b \to s$ and $b \to u$ transitions (charmless B decay) and color-suppressed B decays, are not negligible and have peaks at the B mass in the M_{bc} distribution. The sum of these distributions is modeled by a Gaussian plus an ARGUS function. The shape of the distributions is determined by a corresponding Monte Carlo (MC) sample.

The M_{bc} distribution of the signal component is also modeled by the sum of a Gaussian and an ARGUS function. All parameters are determined from the $B \to X_s\gamma$ signal MC simulation, except that the mean of the Gaussian is extracted from a fit to $B \to D\pi$ decays, described below. Our nominal signal MC contains a $B \to K^*(892)\gamma$ component and an inclusive $b \to s\gamma$ component with $M_{X_s} > 1.15$ GeV/c^2. The ratio of the two components is based on the branching fraction for $B \to K^*(892)\gamma$ measured by Belle [15] and the PDG value of $\mathcal{B}(B \to X_s\gamma)$ [16]. The X_s system of $b \to s\gamma$ is modeled as an equal mixture of $s\bar{d}$

and $s\bar{u}$ quark pairs, and is hadronized using JETSET [17]. The M_{X_s} spectrum is fitted to the model by Kagan and Neubert [18] with the b quark mass parameter $m_b = 4.75 \text{ GeV}/c^2$.

Before discussing the extraction of A_{CP}, we elaborate on the signal modeling. We create alternative signal MC samples in which the $K^*(892)\gamma$ fraction is varied by $\pm 1\sigma$ or the b quark mass parameter is varied by $\pm 0.15 \text{ GeV}/c^2$. We account for the uncertainty in the hadronization process by preparing an alternate MC sample wherein B candidates with $M_{X_s} > 1.15 \text{ GeV}/c^2$ are selected or discarded at random to match the fractions of such candidates observed in the data having between one and four pions. We prepare other such samples wherein the proportion of selected B candidates without a neutral kaon or pion matched the value seen in data; the correction is modest for all modes except $K\pi\gamma$ (which contributes 32% in the MC but 12% after correction). The systematic error estimate based on these samples is described below.

In the pseudo-reconstruction analysis of $B \to X_s\gamma$, the flavor of the B meson is "self-tagged" when the net charge of the X_s system is non-zero or the X_s system contains an odd number of charged kaons. Otherwise the flavor is "ambiguous." Because we have three possibilities for the flavor tag, there are three ways to tag the flavor incorrectly: w_1 is the probability of classifying a self-tagged event as a self-tagged event of the opposite flavor; w_2 is the probability to classify an ambiguous event as self-tagged; w_3 is the probability to classify a taggable event as ambiguous. For example, w_2 refers to the case when a $B^0 \to K_S^0\pi^+\pi^-\gamma$ event is tagged as a $K_S^0\pi^+\pi^0\gamma$ event, and w_3 refers to the case when a $B^+ \to K_S^0\pi^+\pi^0\gamma$ event is tagged as a $K_S^0\pi^+\pi^-\gamma$. The effect of the flavor dependence of the wrong tag fractions is negligibly small, and is included in the systematic error from the $B \to D\pi$ study described later.

The formula to calculate A_{CP} is then $A_{CP} = D A_{CP}^{\text{raw}}$ with the dilution factor $D = (1 - w_2 - w_3)/[(1 - w_2)(1 - 2w_1 - w_3)]$ and the raw asymmetry $A_{CP}^{\text{raw}} = (N_- - N_+)/[N_- + N_+ - (w_2/(1 - w_2))N_0]$, where N_- (N_+) is the number of events tagged as originating from a b ($\bar{b}$) quark, and N_0 is the number of events classified as ambiguous.

The three wrong tag fractions are estimated using signal MC, and thus are model dependent. We calculate the wrong tag fractions for the collection of signal MC samples described earlier, and extract the systematic errors in the wrong tag fractions from the changes in w_i as the model is changed. We find $w_1 = 0.0206 \pm 0.0027$, $w_2 = 0.248 \pm 0.020$ and $w_3 = 0.0067 \pm 0.0013$, resulting in a dilution factor of $D = 1.041 \pm 0.006$.

Figure 1 shows the M_{bc} distributions for events that are classified as b-tagged, $\bar{b}$-tagged and ambiguous, respectively. The distributions are fitted with signal, $q\bar{q}$, $B\bar{B}$ and rare B components. We assume the shapes of the three components are common for b- and $\bar{b}$-tagged classes, distinct from those for the ambiguous class. In the fit, the numbers of events from the $B\bar{B}$ and rare B background in the signal region are fixed to be 39.3 (9.2) and 35.4 (3.3) for the common b- and $\bar{b}$-tagged classes (ambiguous class) using the MC prediction, while the normalization of the $q\bar{q}$ component is allow to float. Signal yields are obtained by integrating the signal Gaussian and ARGUS functions in the signal region. We find the signal yield in each class to be $N_- = 393.2 \pm 25.9$, $N_+ = 392.0 \pm 25.9$ and $N_0 = 52.8 \pm 9.6$, resulting in $A_{CP} = 0.002 \pm 0.050$.

The systematic errors are studied using a $B \to D\pi$ control sample. D mesons are reconstructed in the same final states as X_s except for the final states to which D cannot decay. Only a mild requirement on the invariant mass of the reconstructed D mesons of less than $1.9 \text{ GeV}/c^2$ is applied, in order to allow cross-feeds between different D decay channels. In the calculation of M_{bc}, the primary pion momentum is rescaled in the same way as the

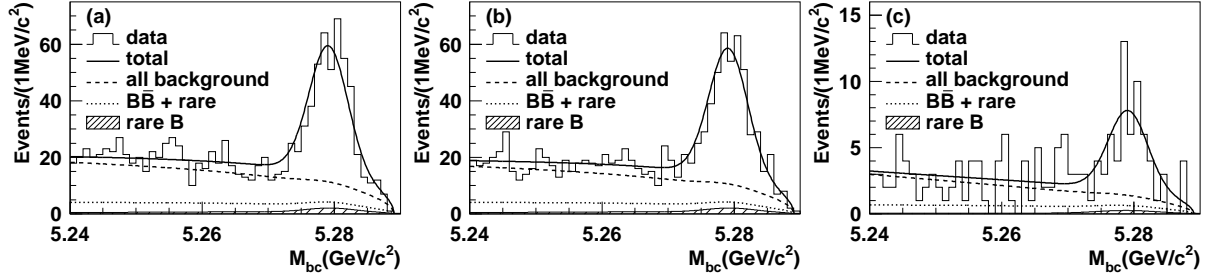FIG. 1: M_{bc} distributions for (a) events tagged as b, (b) events tagged as $\bar{b}$ and (c) events classified as ambiguous. Fit results are overlaid.

photon in the $B \to X_s\gamma$ reconstruction.

In order to check the validity of the signal M_{bc} shape obtained from MC, we compare the M_{bc} distribution for $B \to D\pi$ data and MC. The data M_{bc} distribution is fitted with the sum of a Gaussian and an ARGUS function plus $q\bar{q}$ and $B\bar{B}$ distributions. The $q\bar{q}$ and $B\bar{B}$ distributions are obtained from off-resonance data and MC simulation, respectively, where each normalization is scaled according to the luminosity. From this procedure, we determine the mean of the Gaussian used to model the signal M_{bc} distribution. We find that the ratio of the Gaussian and ARGUS function agrees between data and MC within the statistical error of 23%.

The systematic error on A_{CP} due to the fitting procedure is estimated by varying the value of each fixed parameter by $\pm 1\sigma$ and extracting new signal yields and A_{CP} for each case. We assign an additional 23% error obtained from $B \to D\pi$ to the ratio of the Gaussian and ARGUS function. The ratio is also varied separately for N_+ and N_- to take into account the possible difference of sub-decay modes between b and $\bar{b}$. We also use the signal shape parameters obtained from each of the signal MC samples described earlier and extract A_{CP} for each case. We set the normalization of either the $B\bar{B}$ or rare B backgrounds to zero and to twice its nominal value to account for its uncertainty. A 50% error is assigned to the Gaussian width and to the ratio of the Gaussian and ARGUS function for the rare B decays, to compensate for our limited knowledge of their branching fractions. The changes of A_{CP} for each procedure are added in quadrature, and are regarded as the systematic error. We obtain a systematic error of 0.014 due to the fitting procedure.

The $B \to D\pi$ sample is also used to estimate the possible detector bias in A_{CP}. We estimate A_{CP} for $B \to D\pi$ using the same method as for $B \to X_s\gamma$. The flavor is determined from that of the D candidate. From the MC study, we find the $B \to D\pi$ wrong tag fractions to be $w_1 = 0.0314 \pm 0.0039$, $w_2 = 0.285 \pm 0.024$, and $w_3 = 0.0225 \pm 0.0033$, resulting in a dilution factor of $D = 1.059 \pm 0.013$. The signal yields are calculated by fitting the data M_{bc} distribution with signal, $q\bar{q}$, and $B\bar{B}$ components with fixed $B\bar{B}$ normalization, and are found to be $N_- = 2125 \pm 60$, $N_+ = 2105 \pm 60$ and $N_0 = 580 \pm 30$, resulting in a CP "asymmetry" of $A_{CP} = 0.006 \pm 0.022$. We therefore assign 0.022 as the systematic error due to detector bias.

In addition, we estimate the uncertainty due to possible asymmetries in charmless B decays. We divide these decays into two groups: those for which A_{CP} has been measured ($B \to K^*\eta$, $K\pi^0$ and $K\rho$), corresponding to about half of the selected charmless B events; and all other decay modes. We assign an A_{CP} of $\pm 30\%$ to the first group (corresponding to around 1σ in each case), and $\pm 100\%$ to the second, assuming the signs of A_{CP} are correlated.
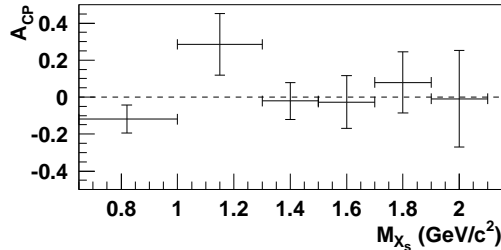
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FIG. 2: A_{CP} for each M_{X_s} bin. M_{X_s} is the reconstructed value of the mass of the X_s system. The data points do not include any correction for the effect of smearing and mis-reconstruction.

The resulting contribution to the measured A_{CP}, 0.014, is taken as a systematic error.

The systematic error on A_{CP} due to the uncertainty of the wrong tag fractions is found to be small. The contribution of the $b \to d\gamma$ process is negligible, because we require the existence of kaons in the final state. This is confirmed by examining MC samples of $B \to \rho\gamma$, $\omega\gamma$ and inclusive $b \to d\gamma$ process [19]; we expect that the contribution of $b \to d\gamma$ to A_{CP} is less than 0.001. The total systematic error on A_{CP} is then calculated to be 0.030 by adding in quadrature the errors mentioned earlier.

In order to examine the M_{X_s} dependence of A_{CP}, we divide the data sample into six bins of measured M_{X_s} and perform the M_{bc} fit for each bin. Figure 2 shows the A_{CP} distribution as a function of M_{X_s}. Here, the systematic error due to the detector bias and possible CP asymmetry in charmless B decays is not included in the error. We find that A_{CP} is consistent with zero for all M_{X_s} values in the distribution. From our MC study, about 2% of the events reconstructed with $M_{X_s} < 2.1$ GeV/c^2 are expected to have a true X_s mass greater than 2.1 GeV/c^2.

In conclusion, the CP asymmetry of $B \to X_s\gamma$ for events with $M_{X_s} < 2.1$ GeV/c^2 is measured to be

$$A_{CP}(B \to X_s\gamma; M_{X_s} < 2.1 \text{ GeV}/c^2) = 0.002 \pm 0.050(\text{stat.}) \pm 0.030(\text{syst.}),$$

consistent with no asymmetry. This corresponds to $-0.093 < A_{CP} < 0.096$ at the 90% confidence level, where we add the statistical and systematic errors in quadrature and assume Gaussian errors. The result can restrict the parameter space of new physics models that allow sizable CP asymmetry in $b \to s\gamma$ [20].

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[20] While this paper was being prepared, a paper by the BaBar Collaboration was submitted that obtains similar conclusions on A_{CP}. [BaBar Collaboration, B. Aubert *et al.*, Phys. Rev. Lett. (to be published), hep-ex/0403035]